

Pre-Deployment Testing, Augmentation and Calibration of Cross-Sensitive Sensors

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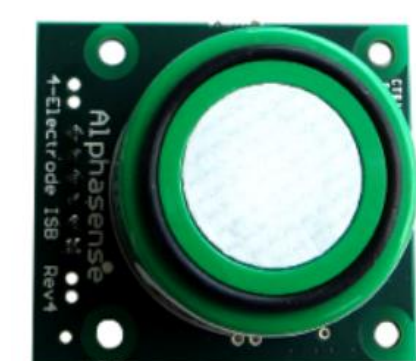


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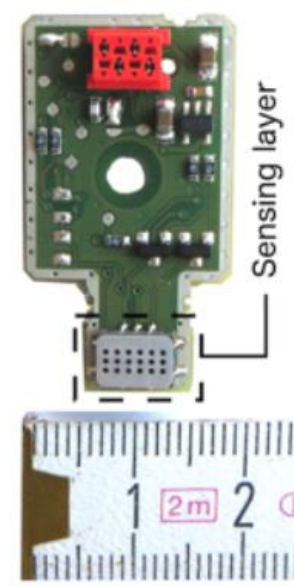


Low-cost Gas Sensors

- Measure concentration of major pollutants: NO₂, CO, O₃, PM₁₀ etc.
- Cheap, small packaging, low-power consumption
- Challenges:
 - Affected by **environmental changes**, e.g. temperature
 - Low selectivity: **cross-sensitive** to multiple pollutants
 - Primarily **designed for higher concentrations** than in outdoor air, e.g. car industry



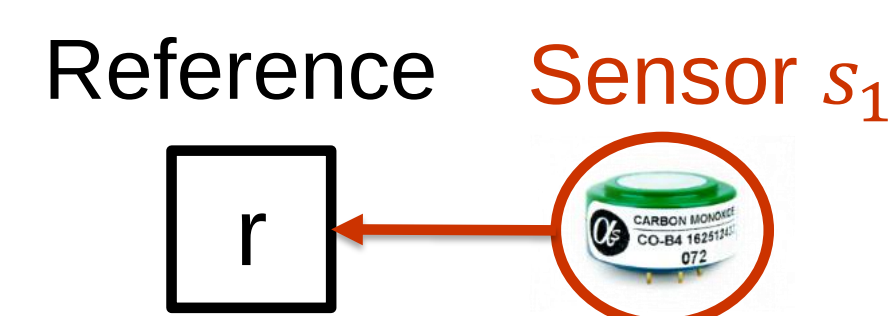
α-sense CO-B4



SGX Sensortech MiCS-OZ-47 O₃

Sensor Calibration

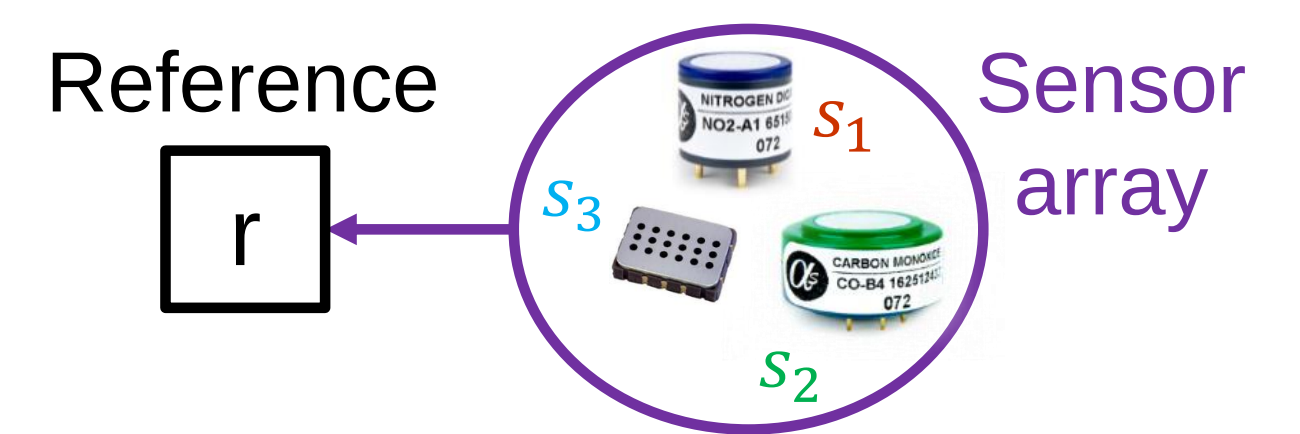
Simple sensor calibration



Calibrate **single** sensor to **single** reference using **Ordinary Least-Squares (OLS)**:

$$r = \beta_0 + \beta_1 s_1 + \varepsilon$$

Sensor array calibration



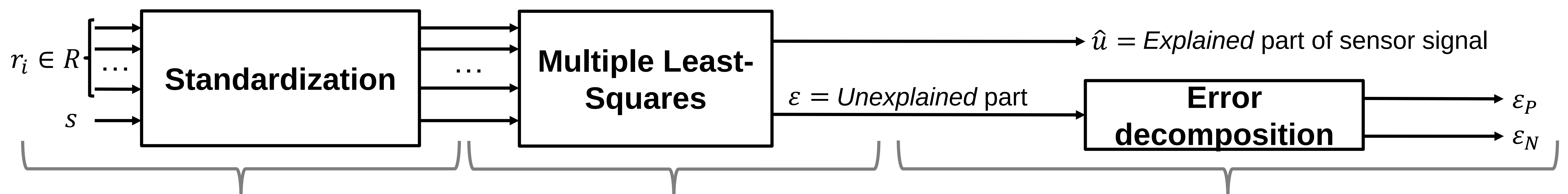
Calibrate **multiple** sensors to **single** reference using **Multiple Least-Squares (MLS)**:

$$r = \beta_0 + \beta_1 s_1 + \beta_2 s_2 + \beta_3 s_3 + \varepsilon$$

Used to compensate for cross-sensitivities

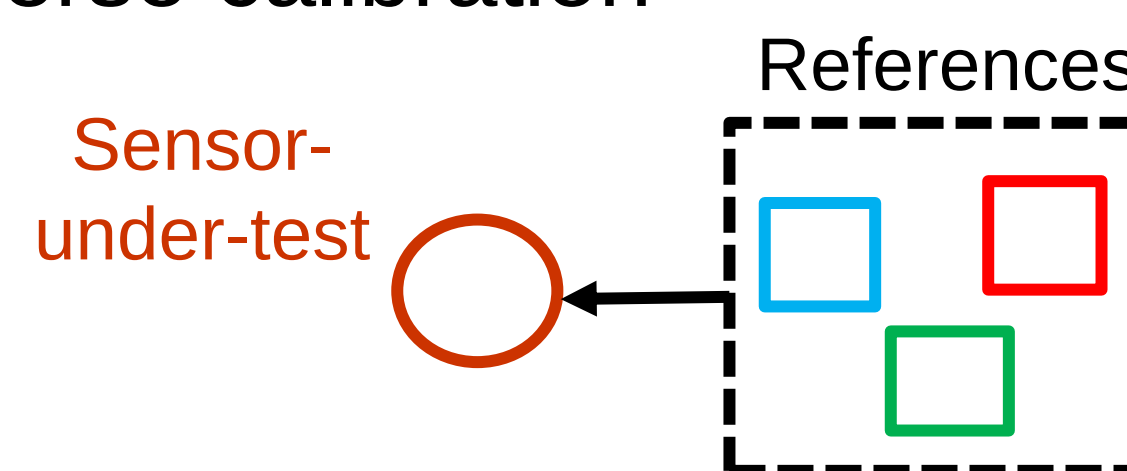
Pre-deployment Testing

How can we uncover all cross-sensitivities and environmental dependencies of a low-cost sensor?



- In-field measurements, e.g. next to high quality monitoring station
- Sensor-under-test: s
- Various reference signals: $r_i \in R$
- Standardization (zero-mean & unit-variance) for scale-invariant results

Inverse calibration

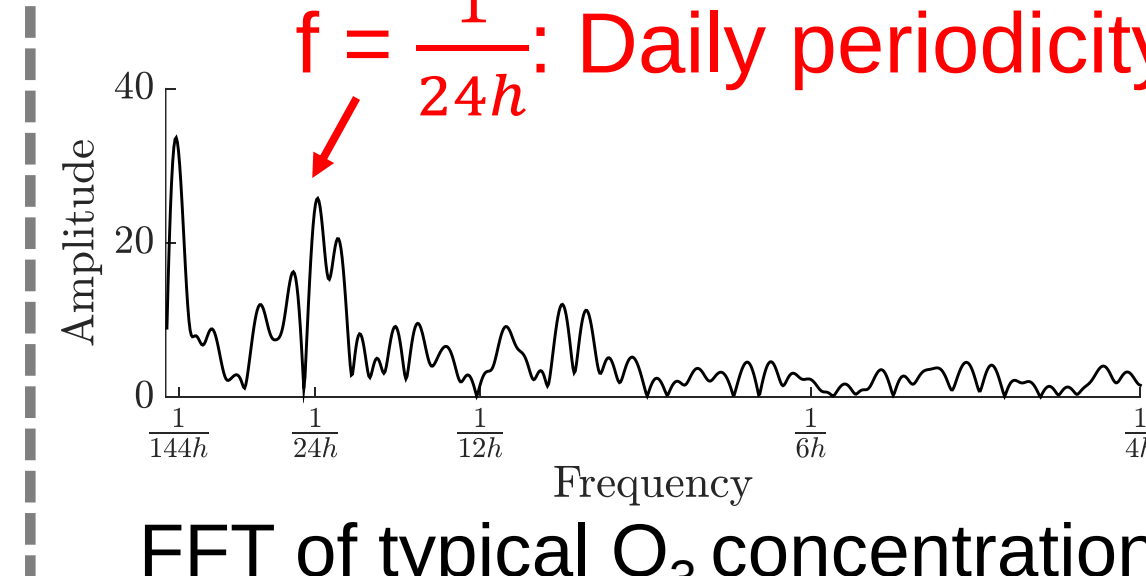


Multiple Least-squares

$$s = \beta_0 + \beta_1 r_1 + \beta_2 r_2 + \beta_3 r_3 + \varepsilon$$

Reason for substantial error can be two-fold

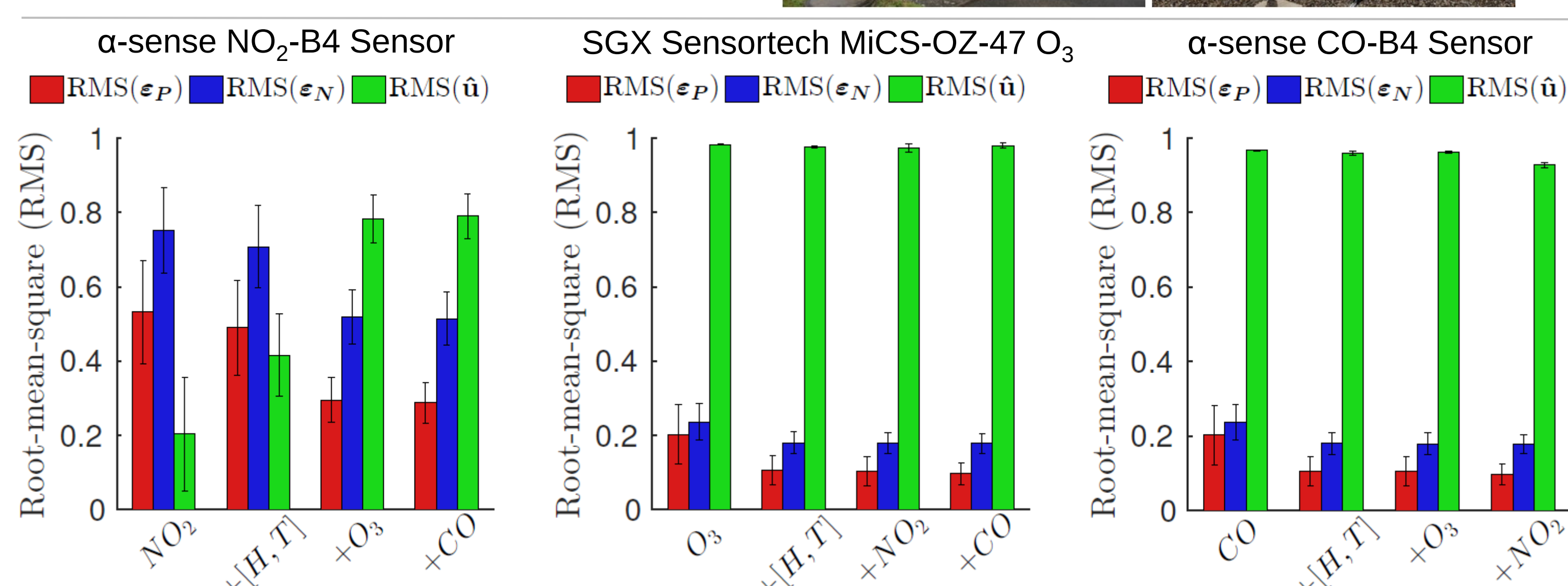
- $f = \frac{1}{24h}$: Daily periodicity $\Rightarrow$ Low-pass filter (cut-off: $\frac{1}{24h}$)
- Low-frequent part ε_P : Uncaptured cross-sensitivities
- High-frequent part ε_N : Sensor noise



Find combination of references that best explains the sensor-under-test by quantifying the amount of captured/uncaptured cross-sensitivities and sensor noise

Experimental Evaluation

Testing of various low-cost sensors at a governmental high-quality station (NABEL) in Dübendorf, Switzerland

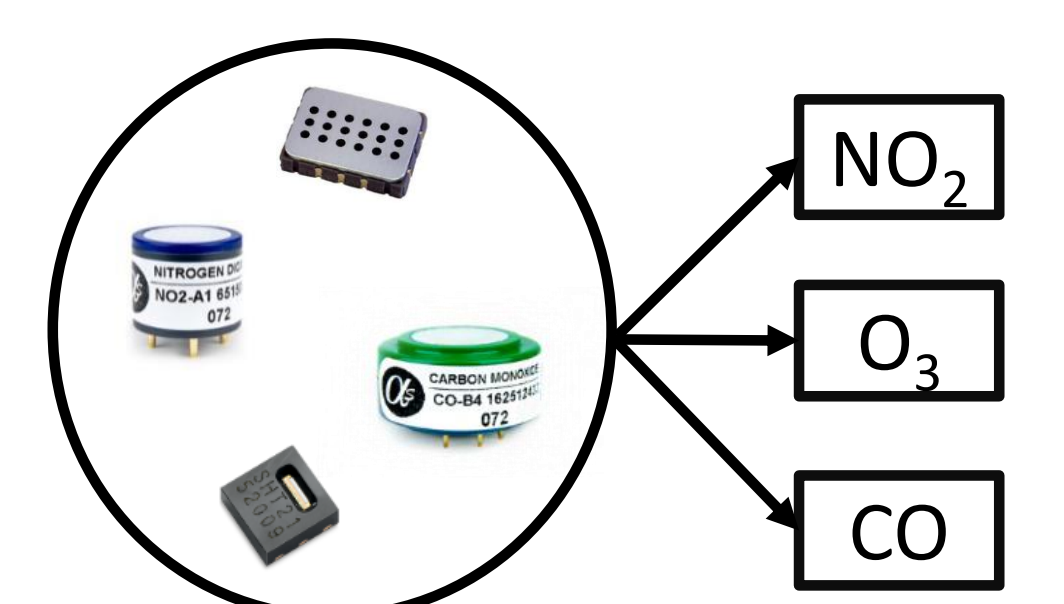


- Quantify captured ($\hat{u}$) & uncaptured (ε_P) cross-sensitivities and sensor noise (ε_N) using root-mean-square value (RMS)
- Gradually extend references to highlight individual effects
- NO₂-B4 is highly cross-sensitive to O₃ and environmental effects
- CO-B4 and SGX O₃ both depend on environmental effects

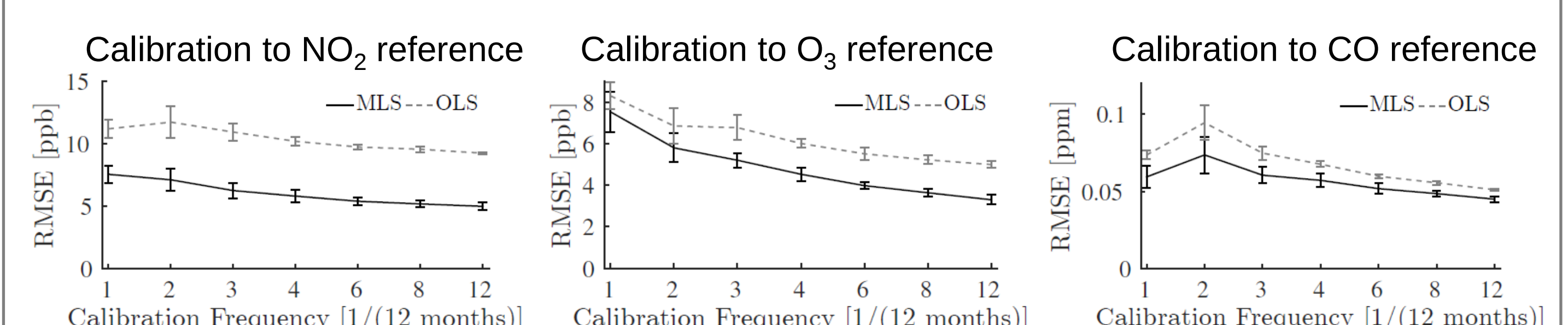
Optimized Sensor Array

Compensating for cross-sensitivities and environmental dependencies improves calibration accuracy and stability of low-cost sensors

- Augmented sensor array
 - SGX Sensortech MiCS-OZ-47 O₃
 - α-sense NO₂-B4
 - α-sense CO-B4
 - Sensirion SHT H & T



Calibration accuracy and stability



- Smaller average calibration error when calibrating sensor array (MLS) compared to simple sensor calibration (OLS)
- Longer stability of sensor array calibration parameters, i.e. MLS requires less re-calibration compared to OLS